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The Mars '07 North Polar Cap Deep Penetration Cryo-Scout Mission

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Abstract—A 2007 Mars North Polar Cap penetration mission is being proposed under the Mars Scout Discovery Program. The Cryobot robotic mole vehicle being developed by a team of JPL engineers would penetrate 200 meters below the polar ice cap in the only known accessible reservoir of water on the planet. The probe would be manifested with a suite of science instruments which will (1) examine the climatic history of Mars as reflected in the layers of ice—the Mars Surveyor Orbiter Camera (MOC) has revealed exciting images of the polar ice cap indicating the layers to be on the order of 1 to 100 meters thick; (2) look for organics and bio-signatures potentially transported via wind and trapped in the ice; (3) examine trapped minerals and understand the chemical make-up of soluble constituents; and (4) provide the first-ever polar cap surface images as well as characterize the polar cap meteorology. Although radioisotope power is baselined for the Mars '07 version of the Cryobot, no decision on the final design of the Cryobot will be made until the environmental review process is complete. Any use of the Cryobot for Mars will conform to all environmental and planetary protection requirements.

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1. INTRODUCTION

The Mars Exploration Payload Assessment Group (MEPAG) report [1] on primary Mars Program science themes cites Life, Climate, Resources, and Preparation for Human Exploration as four elements of a "Follow the Water" strategy. By probing the only known accessible reservoir of water on the planet, Cryo-Scout addresses each aspect of this strategy [2]. Each of the primary science goals are summarized below:

1.1 Life

Cryo-Scout will seek chemical and structural biosignatures of present or preserved life in ice and melt-water, inventory energy sources and some forms of carbon, and infer past hydrological activity from the climate record. [MEPAG I:A2(b,c), A3(a), A4(d), A5(a-c), and B3(a)].

1.2 Climate

Long-term trends in Martian climate may be due to planetary obliquity excursions, global dust storms, volcanism, and hydrothermal or impact events. Cryo-Scout will help decipher the physical and chemical records of past climates encoded in the stratigraphy. Present-day environmental cycles will be monitored on the surface. [MEPAG II:A1(b,f), A3(new), B1(c), B2(c)].

1.3 Resources

Composition of dust-laden melt-water may reveal the evolution of sedimentary processes and volcanic contributions to the record. The surface station characterizes surface/atmosphere interactions. [MEPAG III:A2(3), A5(c,d)]

1.4 Preparation

For human explorers, the ice cap may represent an inexhaustible source of life-giving water and the raw ingredients for fuel. Cryo-Scout will investigate the accessibility and utility of this resource, and determine the engineering properties of the ice itself. [2] Chemical sensors will measure soluble constituents of Martian dust as it soaks in melt-water, and the observed stratigraphy may reveal the historical frequency of dust storms. [MEPAG IV: A2(a,c,g), A4(b,d), and A6(a,e,h,j,k)].

Each of the above science themes will be implemented using a suite of science instruments contained both on the lander deck and within the Cryobot vehicle. A spectroscopic imager will take surface images and analyze surface material in the immediate area around the lander. A meteorology station will measure frost-point, pressure, temperature, wind, and dust-fall accumulation.

As the Cryobot descends hundreds of meters, the ice column will be examined. Climate history/deposition cycles will be studied using optical imagers, acoustic signal propagation, and possibly mass spectroscopy, UV fluorescence, amino acid detection, and/or elemental abundances will allow bio-signatures to be identified. Electrochemical sensors or Raman spectroscopy will provide the basis for understanding the chemistry of the deposited material and melt-water.

This unique mission, employing advanced subsurface robotic technology and a rich suite of both surface and subsurface instruments, offers NASA a first-time opportunity to finally "follow the water" and characterize/sample a completely untouched frozen-in-time environment that may yield answers to many of the mysteries Mars scientists have been trying to solve for decades.

2. Scientific Foundation

This section discusses the science goals in greater detail along with proposed strategies for making science measurements. An array of instruments is presented that can meet the science requirements and potentially fit within the Cryobot volume and power constraints.

2.1 Science Goals

Accumulation or removal of moisture from the polar cap is part of a global exchange process that involves both poles and lower latitude ground ice deposits [3]. Both the amplitude and the sign of accumulation/ablation are believed to vary with the Martian orbital elements, particularly the obliquity cycle. Periods of high obliquity tend to level global temperatures, favoring transfer from the poles to low latitudes. Periods of low obliquity increase meridional temperature gradients, favoring accumulation of water ice. As obliquity oscillations have been strongly damped for the past 300 KY [4], it is possible that the precession or perihelion (~ 50 KY period) may have dominated recent variations. Oscillations in eccentricity are believed to exert a lesser effect than either obliquity or precessional variations.

Since dust probably accumulates with water ice at the poles, the variations in annual net water deposition rates may correspond to variations in dust loading. The actual rates of deposition, and thus the chronological scale of the record, are not well understood. Estimates of current accumulation rates range from 0.01 to several kilometers per MY [5]. There are four main methods for age dating ice, all of which rely on counting yearly layers in the vertical section [6]: (1) stable isotopes ($^{18}O/^{16}O$), (2) resistivity measurements, (3) acidity banding, and (4) visible banding (including ice fabric, density, or volcanic/clay particulates). Ice cores up to 2 miles deep in Greenland have used these methods to date ice up to 10,000 years in age and has been shown to be accurate to better than 2% by comparison with other geologic strata. Layering has been counted through 100,000 years, though errors increase to 10%. Other methods include observing layers of meteoritic microparticles [7], radioactive decay methods [8], predicting burial rates from modeled glacier dynamics [9], and radio reflection from conductive (acidic) ice layers [10,11]. A summary of methods is shown in Table 1 [6].

Table 1. Different Methods of Age Dating in Ice and Approximate Time Ranges.

General Category	Specific Technique	Time Range (Years)
Stratigraphy (2 types)		
Reference Horizons		
	Stable Isotopes (^{18}O or ^{2}H)	500,000
	Volcanic Ash/Dust	>200
	Soluble Volcanic Debris (Acidity)	>200
	Radio Reflection Layers	10,000
	Fission product fallout	>1954
Seasonal Variation		
	Ice fabric, density, mineral deposits	100,000
	Radio-isotopes	>1954
	Micro-particles	10,000
	Stable Isotopes (^{18}O, ^{2}H, trace elements)	15,000
	Long period $\delta(^{18}O)$ cycles	100,000
Radioactive Decay		
	^{3}H and ^{210}Pb	100
	^{32}Si and ^{39}Ar	1,000
	^{14}C	25,000
	^{10}Be, ^{26}Al, ^{36}Cl, ^{53}Mn, ^{81}Kr	>100,000
Glacier Dynamics		
	Flow models	10,000
	Vertical velocity observed in borehole	?

Adapted from *Hammer et al.*, 1978 [12]

Life detection is an important science goal achievable with the Cryobot. It is believed that there are some universally measurable parameters by which one may recognize life as distinct from non-life in a non-Earthcentric way. The two primary parameters are the chemical nature and associated structural features of the organism, even when the structural feature may be as simple as the three-dimensional distribution of the defining chemistry [12]. This strategy necessitates characterization of the planetary materials so the distinctions can be made.

Experience with terrestrial ice caps suggests that if there were past or extant microbial life on Mars, a sample of that life might well be preserved within the polar ice. Wind blown microbes attached to dust substrates may be trapped within the layers of ice. Even in the cold desert conditions of Antarctica there are organisms living within the ice. The sampling approach of the Cryobot is ideal for two reasons. It is recognized that in order to increase the chances of finding either the structural or chemical signatures of life one must be able to sample a large volume of material. By penetrating the polar cap and sampling the melt water column continuously, particularly in areas where dust substrate and chemical nutrients abound, a very rich and significant sampling environment is accessible. A second advantage to this sampling strategy is the relative chemical simplicity of the ice sedimentary system, which is essentially mono-mineralic. If the basis for our non-Earthcentric life detection strategy is the requirement that we be able to distinguish anomalous chemical and structural features from those of the sedimentary background, the greater the contrast ratio, or signal-to-noise of the candidate chemical and structural biosignatures, the cleaner the measurement.

Some of the distinguishing chemical signatures of life that one might measure are: elemental abundances, particularly elemental ratios, stable isotopic fractionation, organic inventory, water content, oxidation state of certain physiologically important metals, and regular temporal fluctuations in any of the above. Structural features could range from as preserved hard parts (e.g., skeletal) to density differences due to microbial weathering of mineral grains in dust particles, to observation of chemical distributions in three dimensions, including redox fronts or other steep chemical gradients.

2.2 Measurement Strategy

The Cryo-Scout system is designed to provide surface measurements as well as sub-surface measurements. Surface measurements will be made off the lander deck with no sampling required. Imaging, both visual and spectrographic, will record polar cap surface features and composition. A meteorology station will record temperatures, pressure, wind, frostpoint, and dust deposition at or near the surface.

The Cryobot will sample the meltwater column as the vehicle melts through the polar ice. The primary measurement strategy will be to optically interrogate the surrounding meltwater/ice column regime. Opacity measurements with high vertical resolution will help quantify dust loading. Red, green, and blue light sources will be complemented by an ultraviolet source to induce mineralogical and organic fluorescence of materials in the ice. Electrochemical measurements will be performed through either direct contact with the melt column, or by wicking small quantities of meltwater into a series of evacuated chambers, to determine the soluble chemistry of embedded solids. These measurements will identify particulate genesis as volcanic, evaporitic, or possibly biological. Measurement of isotopic ratios may allow a crude chronology estimate. A simple off-angle optical measurement will determine total turbidity. Climate history will be examined by looking at the periodic variations in density of particulate material as evidenced in the ice stratification. Ice and humidity may have protected organic molecules from destruction by oxidants. Such organics will be observed directly in the ice by fluorescence, or through in-situ analysis of volatiles. Microscopic and electrochemical analysis of particles in the ice column will provide records of particulate geometries as well as chemical constituency.

2.3 Instrument Options

The potential suite of instruments includes vehicle state sensors as well. Table 2 shows the relationship between the desired measurement and possible supporting instruments.

Table 2. Science Measurement and Supporting Instrument Suites.

Science Measurement	Instrument Options
Climate history	Optical imager Acoustic imager (vehicle obstacle avoidance/navigation)
Polar surface	Surface visible/spectroscopic imager (will image outside area of plume contamination around lander) Meteorology mast/sensor suite
Organics/ Bio-signatures	UV fluorescence imaging and spectroscopy Tunable-diode lasers DUV vibrational spectroscopy IR reflectance spectroscopy
Mineralogy	Electrochemical sensors (ions, pH, redox, conductivity) Optical turbidity measurement Raman spectroscopy

3. Mission Summary

This section provides the reader with an overview of the mission. The mission implementation strategy is provided via a discussion of carrier vehicle selection, supporting site characterization, lander design, and payload envelope description.

3.1 Vehicle Carrier/Dynamics

The Cryo-Scout north polar cap mission has two Type 2 trajectory launch dates that fit with the current launch profiles. Both opportunities launch on September 4, 2007. Landing opportunity (1) lands at 85.2° N. latitude on July

18, 2008. Landing opportunity (2) lands at 87.2° N. latitude on August 18, 2008. While both landing sites are acceptable, the July 18 target was picked because it allowed the greatest surface science time margin.

The planet orbital entry energetics (C3) are favorable because the entry angle of inclination is towards the north polar cap. The C3 is between 14 and 16.3 Km^2/sec^2. For both of these C3 values a Delta 2925-9.5 launch vehicle allows injection of 975 to 1000 Kg of payload into Mars orbit at a reasonable cost. The current best estimate of total injected payload for Cryo-Scout is 875 Kg (including margin), which is well below the 975-Kg constraint.

3.2 Lander Design/Payload Deployment

The lander selected by the Cryo-Scout team is a re-design of the Mars '01 Lockheed-Martin lander, retrofitted and upgraded per the NASA Young Commission recommendations. The lander separates from the cruise stage on entry. A parachute slows the lander entry velocity and is jettisoned at approximately 1 Km above the surface at which time the reverse thrusters are fired in preparation for soft landing. The thrusters are shut off approximately 1meter above the surface to minimize plume induced surface ablation. Figures 1 and 2 show both the north polar cap region and the approximate landing ellipse for the 85° N latitude landing site. This site is ideal in that Mars Surveyor MOC/MOLA (Mars Orbiter Laser Altimetry) images show the surface to be reasonably flat and free of large obstacles (i.e., rocks/ ridges) at approximately 3-m scale resolution. After touchdown, the science payload is initialized in preparation for deployment.

Fig. 1. Mars North Polar Cap.

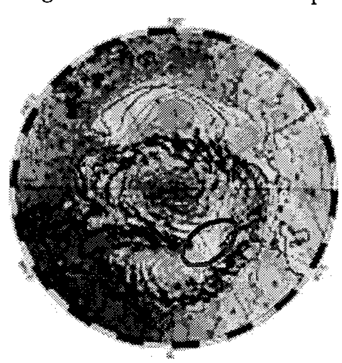

Fig. 2. Mars Polar Cap Landing Site Shown as Large Flat Yellow Area at 85–90°.

Once the lander communication subsystem establishes contact and synch with the Deep Space Network (DSN), all payload elements are initialized and checked. All three major science payload elements [surface stereo imager, meteorological station (MET), and Cryobot] are deployed vertically. The surface stereo image is attached to a semi-rigid mast and is deployed like a jack-in-the-box. At full extension, the imager is approximately 1meter above the deck of the lander [see Mars Volatiles and Climate Surveyor (MVACS) '98 configuration]. The meteorology mast is stowed horizontally across the deck next to the probe. It is deployed using a passive spring action, which moves the mast into a vertical position also approximately 1 meter above the deck. The probe is raised from its horizontal stowed configuration in the opposite direction from the MET mast and moves to a vertical position with its nose centered over a cutout in the outside edge of the deck circumference. On release, a passive spring absorbs the g-forces as the probe falls nose first toward the surface. The probe gently contacts the ice surface in its fully deployed configuration, ready to start penetrating the ice crust.

3.3 Lander/Orbiter Communication Options

The Mars telecommunication infrastructure planned for the 2007 timeframe suggests that there will be two relay orbiters available that have a high polar inclination. The two orbiters and their attributes are shown in Table 3.

The total Cryo-Scout data volume includes both lander and Cryobot state sensor data (e.g., attitude, rate, temperature, pressure, etc.) as well as instrument data. The total system data volume has been conservatively estimated to be 240 Mb/sol. As Table 3 indicates, the Mars Reconnaissance Orbiter (MRO) has sufficient on-board storage to accommodate the complete daily data volume of Cryo-Scout. Given the large number of passes, the data can be relayed back to Earth in 23-Mb chunks in order to not interfere with other science instruments that are on the orbiter. As backup, the Centre National d'Études Spatiales (CNES) orbiter could also relay data in the event of an MRO failure. Additionally, the large number of orbiter passes provides substantial margin for re-transmitting data in the event of an inadvertent transmit interrupt or character corruption.

The lander deck imager and MET station will store their respective data in the lander computer memory. The Cryobot state data and instruments will transmit their data sets back to the lander via an optical fiber interface embedded in the 100- to 200-m tether which is deployed from the rear of the vehicle as it descends. In this manner, the melt column can refreeze behind the vehicle without causing potentially high-tension stresses on the communication/power cable. The tether is approximately 2.5 mm in diameter.

3.4 Lander/Cryobot Power Options

During the calendar year 2001, NASA opened up the 2007 mission to using radioisotope power sources (RPS) [13]. The original design of the Cryobot focused on an Europan ice sheet penetration of several kilometers. The combined

Table 3. Polar Orbiting Communication Platforms for 2007.

Orbiter	Antenna Type	Orbit Inclination (deg)	Orbit Altitude (Km)	Passes/sol	Mb/sol
Mars Reconn	Omni	2.9	400	12	275
CNES Netlander	Omni	94.9	1000	10	100
Note: Data rates assume 1W of power for Omni antenna. All options have a 3-db operating margin.					

orbital position of Europa relative to the Sun and extended mission cycle (i.e., on the order of 1 year) demanded that a radioisotope power source be used. The application of RPS to Mars is not as critical since Mars does have reasonable solar insolation. However, given that the Cryo-Scout mission site is located at a high latitude, therefore causing the sun inclination above the horizon to be low (approximately 25°), and considering lander mass/volume constraints, it would be desirable to use RPS for Mars as well. Therefore, RPS is baselined for the Mars '07 Cryo-Scout mission with caveats. The RPS material targeted for use in '07 is Galileo/Cassini vintage spacecraft Pu238 general-purpose heat source (GPHS) radioisotope thermal generators (RTG). At least four (4) GPHSs are needed to provide a minimum of 800 Wt (50 We) power to both initiate melt and operate the on-board vehicle control system (CPU, A/D, signal conditioning, timer, power switching), state sensors, and instruments. The RTGs allow the probe to melt at approximately 0.1 to 0.3 m/hr in −110 °C ice, depending on ice impurities and percentage of CO_2. There are two caveats associated with using RPS: (1) off-the-shelf RTGs can only be used if there is sufficient RPS material to support Europa Orbiter (the only outer planets approved mission for the 2008 timeframe); and (2) off-the-shelf RTGs can only be used if the subsequent launch re-approval cost/schedule fit within the existing Discovery program cost cap.

In the event the use-of-RPS caveats are violated, an alternative hybrid photo-voltaic (PV)-Stirling-Li-ion battery system has been designed which will convert the Mars solar insolation into electrical power for transfer via tether to the probe. Although not as efficient as RPS in heat generation, the low polar cap ice temperatures minimize power loss down the tether, which facilitates application of most of the lander provided power for the probe. The hybrid power system utilizes the advantage of having sunlight for a complete Martian sol as well as an active deployment/tracking system to maximize power conversion. The solar array is nominally 1 to 2 m in width, with a total area of 10 m^2. The Stirling generator utilizes two small GPHS bricks and, when coupled with the Li-ion rechargeable batteries, provide cyclic peak power for melting within the mass and volume constraints of the lander. It is not clear yet whether or not the Stirling generator is essential to the viability of the power system. To maximize efficiency, triple junction PV cells will be used (i.e., 26–28%). Current solar insolation models show a maximum sun inclination at the beginning of the mission of 28° and minimum of 22°. By the end of the mission (i.e., nominally 75 days) the maximum inclination will be 22.5° and the minimum will be 13.5°. Additionally, continued modeling of the probe fluid dynamics show that the rear of the probe will start to re-freeze after approximately 2 hours during the "re-charge" power cycle. The battery recharge period is projected to be a maximum of approximately 2 to 3 hours. This means that operating the probe cyclically will not cause huge re-start problems and subsequent descent delays.

4. Instrument Delivery Approach/ Current Status

This section describes the planned Mars Cryobot/instrument configuration, and also provides the reader with a status on the current system build of the prototype probe.

4.1 Mars '07 Cryobot Configuration

The Mars 07 Cryobot system is being designed for optimal performance in order to minimize power and mass. The projected Mars north polar cap ice temperature is on the order of −120 °C. In order to sustain a constant penetration rate at −120 °C, current models suggest that it would be desirable to employ closer to a kilowatt of thermal power. The kilowatt magnitude power input allows formation of a 1-mm melt-water jacket around the probe. Previous calculations on Cryobot volume requirements [14] showed that in order to package control electronics, heaters, sensors, communication tether, and science instruments the vehicle needed to be at least 12 cm in diameter, and no more than 1 to 1.25 m long in order to fit within a Delta 2925-9.5 aeroshell. Existing fluid dynamic models [15] show that if the power were to be shut off at any time during the melt phase, the probe would start to refreeze around the rear of the probe at 1 m aft (i.e., the volume of the probe having the least thermal mass) within 2–3 hrs. One option being considered is to reduce the size of the probe diameter and length. Alternatively, the previous power options discussion showed that existing power models strongly suggest that a peak power melt cycle of 1hr "on" and 2 hrs "off" will allow the probe to maintain an active melt cycle without becoming entrapped. In the worst case, the rear 20–30 cm of the probe start to refreeze at the end of 2 hours, requiring activation of the rear shell heaters to free the probe. The following components make up the complete probe [14]:

1. Nose
   - Water jet nozzle
   - Acoustic imaging system (4 transducers; 1 short range (2 cm), 3 long range (2–3 m))
   - Four quadrant passive resistance heaters
   - Heat conductive copper quadrant inserts
   - Ceramic insulation between heaters
2. Pump bay
   - Melt-water pump
   - Pump motor

- Melt-water reservoir
- Immersion heaters (2)
- Water jet plumbing

3. Pressure Vessel
   - Forward/aft bulkheads (o-ring sealed)
   - Control electronics/cabling
   - Science instruments
   - Imager/UV laser window
   - Primary tether connector
   - Shell heaters (4)
4. Tether bay
   - Copper/fiber-optic power and com tether (0.100-in diameter, 300 m long)
   - Tether connector
   - Tether brake and encoder

The combined mass of the probe nose and reservoir/pump bay allows the probe center-of-mass to be slightly forward, making the probe nose heavy very similar to lawn dart. The computational architecture performs all power control, sensor fusion functions, vehicle control (i.e., navigation), and science instrument operation. The complete vehicle control flow process was described in detail in an earlier publication [14] and is, therefore, only summarized here. The Mars ice environment suggests that dust impregnated ice will be encountered per Mars Surveyor MOC images. In the near-surface firn ice, the passive heaters will be required due to the porosity and subsequent interstitial loss of melt-water. However, in the deeper more dense ice a thin melt-water envelope will be retained around the probe allowing the pump bay to fill. The on-board vehicle sensors will sense the water level in the pump bay and provide the necessary signal to activate the water jets. The water jetting is particularly needed to move dust/particulates away from the nose of the probe. The forward-looking acoustic imager will sense the melt front obstacles and sediment lenses. Vehicle navigation around obstacles is initiated by using differential heating. Activation of two of the nose passive heaters initiates growth of a convective heat/melt layer on that side of the probe. Activation of the opposing shell heaters initiates growth of a convective melt layer on the opposite upper surface of the probe. This opposing nose/shell heater operation allows the probe to slowly rotate away from its vertical descent vector, or move back to the vertical after a turn. The instrument bay sits above the pump bay. The ice/melt-water column is observed through a window in the shell. Meltwater is wicked into small chambers from the pump bay. Electro-chemical measurements are made using micro-electrodes in contact with the melt-water.

4.2 FY'01 Prototype Cryobot Description/Status

The FY'01 prototype vehicle is shown in Figures 3 and 4. Figure 3 shows a three-dimensional graphic of the complete probe in its current configuration. Figure 4 shows the actual Cryobot hardware currently being tested in the laboratory. There are two science instruments currently integrated into the design. A small camera and illumination source allow both images and turbidity measurements to be taken within the melt column. An ORION chemical sensor mounted in the pump bay samples the melt-water and provides data on pH, temperature, pressure, and conductivity. Figure 5 shows the camera, and Figure 6 shows the chemistry sensor embedded lengthwise in the pump bay.

Fig. 3. Three-dimensional Graphic of Complete Probe in its Current Configuration.

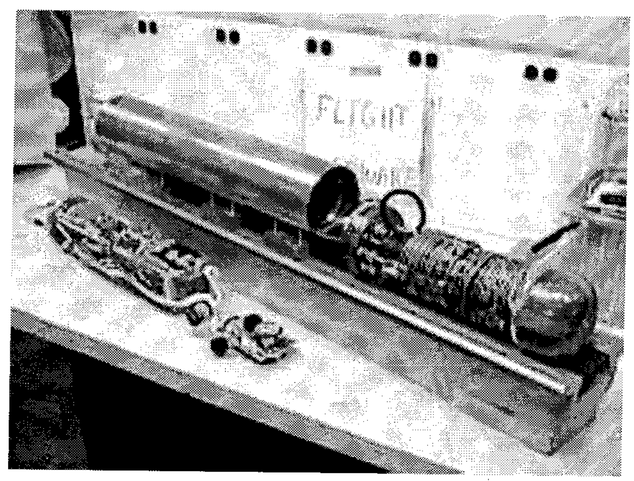

Fig. 4. Break-out of Prototype Cryobot System Hardware Including Mini-Camera (Foreground).

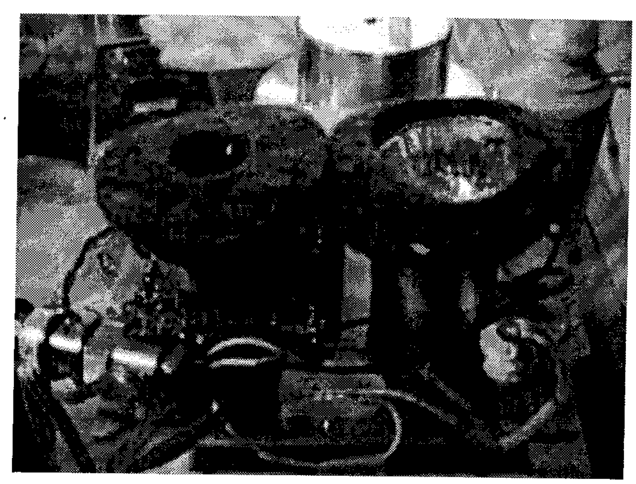

Fig. 5. Camera with Light Source.

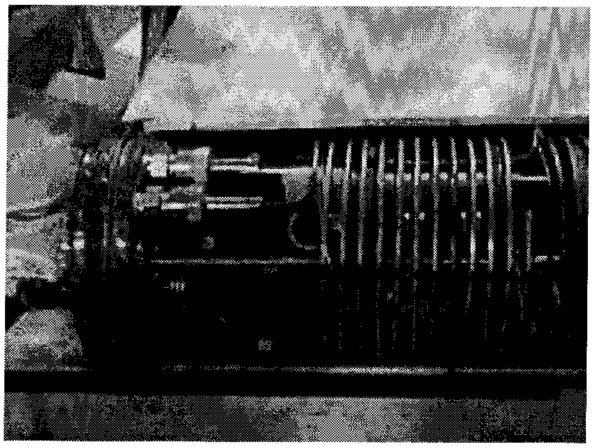

Fig. 6. Chemistry Sensor Embedded in the Pump Bay.

5. VEHICLE TEST RESULTS/PLANS

5.1 Laboratory Test Results

One of the primary goals of the FY'01 research was to start to study and characterize vehicle melt dynamics in the presence of varying degrees of dust/soil in the ice. Several tests were run using dust/particulates in the range of 10 to 750 microns at varying particulate loading levels (e.g., 10% by volume). Figures 7, 8, and 9 are example plots of vehicle melt progression (cumulative depth in cm) as a function of time, for a given particulate size and volumetric loading. Figure 7 shows that with the 750-micron particulates, the vehicle comes to a complete stop after 10 centimeters. On closer examination, it was found that the 750-micron particulates are dense enough to sink to the bottom of the borehole and form a thermal insulation boundary—i.e., no heat is transferred from the nose to the melt-front. Even with active water jetting, the denser particulates do not circulate away from the nose. This test case was considered "worst case" and not the likely environment expected for Mars. The more likely case for Mars is particulate loading on the order of 10microns. Figure 8 shows that with the 10-micron dust, the active water jetting system was able to circulate the material away from the nose. The curve shows that the probe continued to melt at a fairly constant rate. Finally, both Figures 8 and 9 show that with the side cutting pockets, the probe is able to continue melting incrementally in steps even with larger particulates suspended in the ice. The results of the laboratory tests were significant in that they initiated a redesign of the water-jetting scheme for the actual Mars probe. By adding three additional downward-canted side jets into the pump bay shell, side pockets can be cut into the melt column in dense sediment regions to allow the heavier particulates to be re-deposited away from the vehicle nose. This new design will allow the Cryobot to accommodate a wider range of dust/particulate sizes. Testing will continue next fiscal year.

5.2 Field Test Results

In order to develop a robust design for a Mars '07 Discovery Scout launch, it was understood that the Cryobot prototype had to be tested in an actual field environment. A field deployment is considered essential for two reasons: (1) the complete robotic vehicle capability (i.e., end-to-end system build/test, passive/active melting, navigation, and science data acquisition) is exercised in a real ice environment containing variable ice structures and contaminants like dust/salts over an extended distance—the vehicle will descend tens of meters, and (2) successful field deployment of advanced technology like Cryobot provides a sound basis for projecting its true technology readiness level (TRL) in preparation for going to full flight design/build. It is important to understand that in any field deployment, one of the most important outcomes is to observe and learn how the actual system behaves (i.e., actual heat transfer efficiency vs. projected efficiency, failure mechanisms, and subsequent vehicle behavior) in a real, non-laboratory environment.

The site picked for field deployment was a large glacier on Svalbard Island, Norway. The JPL team was composed of five engineers (the original development team), one JPL Mars scientist, one Caltech glaciologist, and a Norwegian guide. The probe was delivered to the Norwegian Polar Institute in Svalbard, disassembled, and completely checked out prior to being moved onto the glacier. Once on the glacier, the system was reassembled. The complete system was composed of the deployment tripod, cryobot, power/communication tethers, generator/power supply, and operator workstation. Figure 10 shows the complete tripod/probe configuration just prior to initiating ice penetration.

The Mars design calls for the tether/strength member to be housed and deployed from the rear of the cryobot. However, for this field deployment, the tether and wire strength member were deployed from a spool attached to the top surface of the tripod. A stepper motor/load cell allowed the cable to be played-out as a function of probe penetration rate and cable tension—very similar to the flight design. The passive heaters were turned on and the probe slowly penetrated the top firn ice layer. Once the probe had penetrated approximately 0.5 m, the ice was dense enough to enable activation of the active water-jetting system. Figure 11 shows the probe in the ice at a depth of about 3 meters. The water-jetting system allowed the probe to melt at a rate of 0.6 to 0.7 m/hr, with a power input of approximately 0.8 Kw at the probe. One of the most interesting observations made during the field test was that the probe appeared to be periodically hanging up. The post-mission disassembly revealed that the probe pump bay contained significant amounts of 10- to 60-micron particulates. This finding was proof that, indeed, the cryobot penetrated several dust/sediment layers during its descent. Over a period of 100–150 hours of operation, probe component failures started to surface. The pump bay heaters failed, resulting in a shift of melt control from heating the water in the pump bay to heating the water in front of the probe, while still operating the water jet. The probe descent rate slowed to 0.3 to 0.4 m/hr. After another 100 hrs of operation, the water jet pump failed, resulting in a shift of melt control to pure passive heating. The probe descent rate slowed to 1 to 3 cm/hr. By the completion of the mission, the cryobot prototype had descended a total of 23 m.

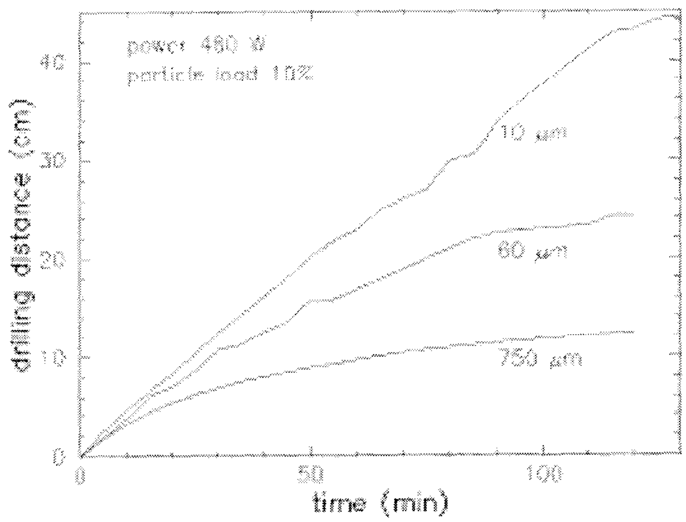

Fig. 7. Passive Melting Test.

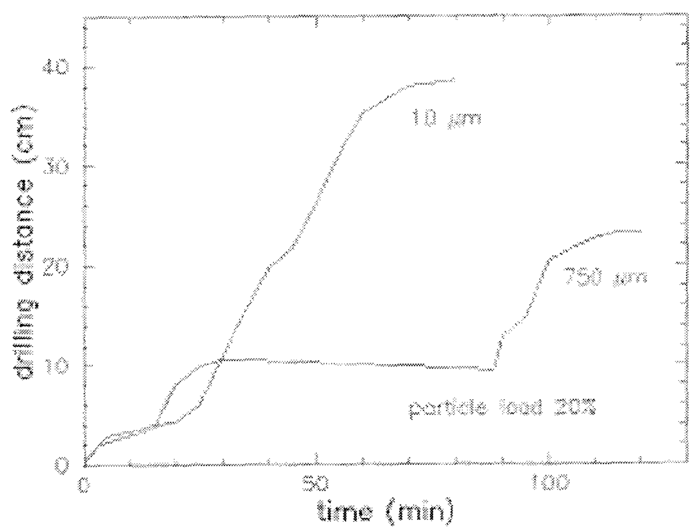

Fig. 8. Active Jetting with Side Pockets Test.

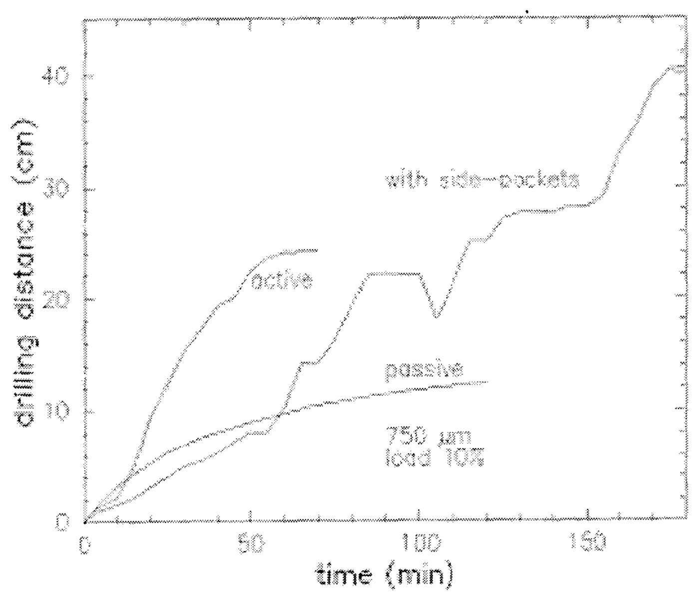

Fig. 9. Active and Passive Melting Test Comparison.

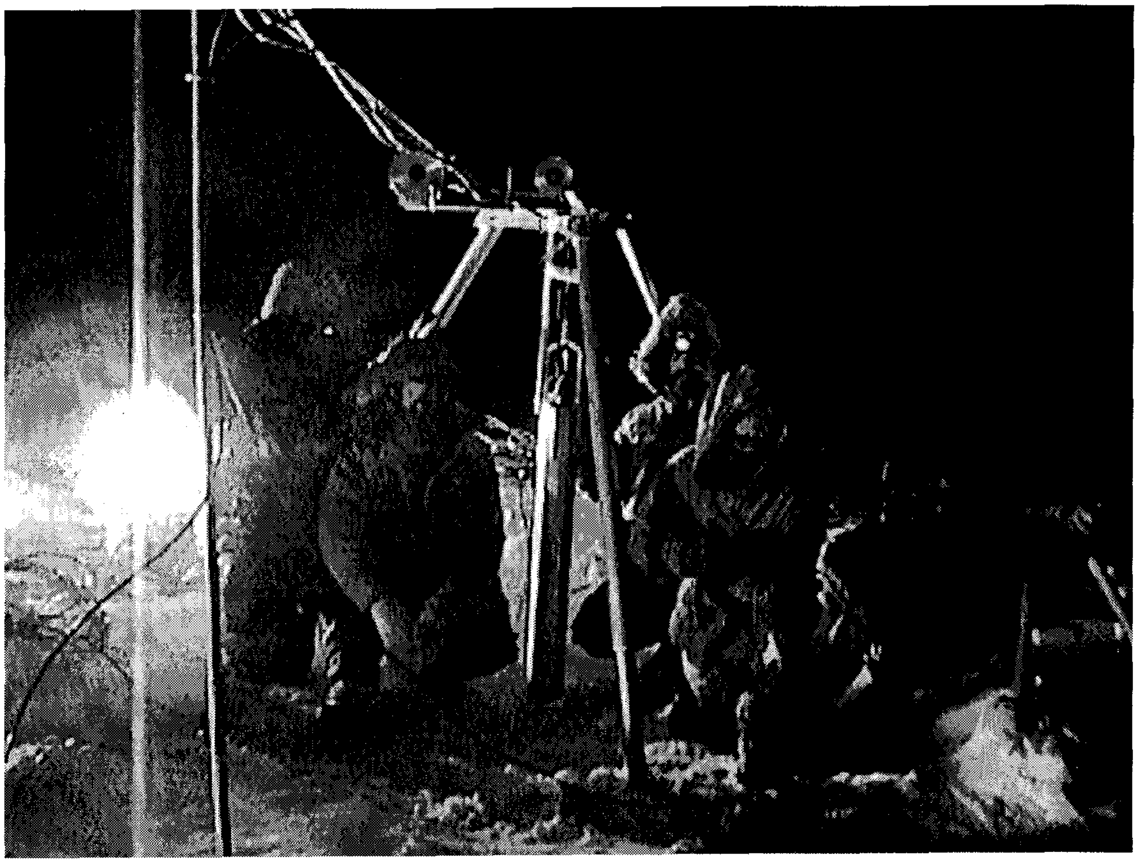

Fig. 10. Complete Tripod/probe Configuration Just Prior to Initiating Ice Penetration.

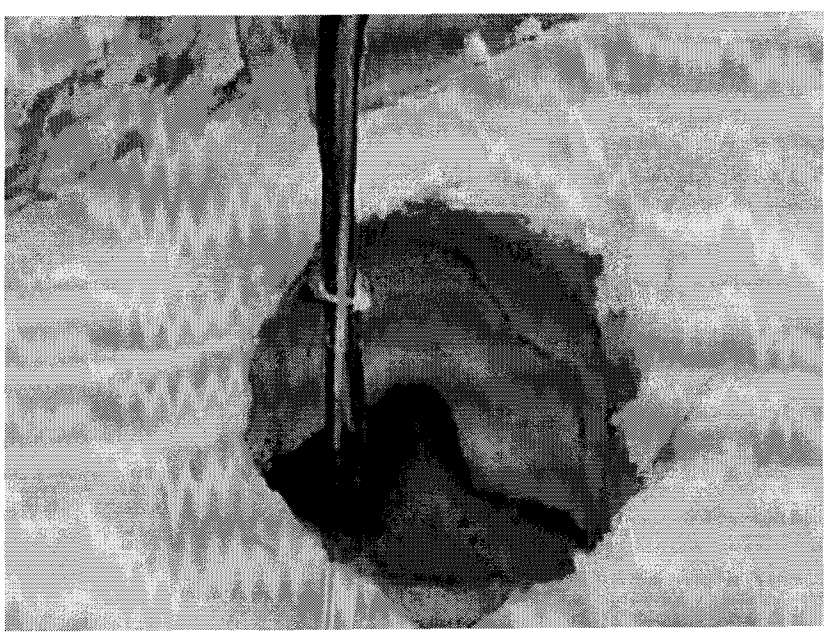

Fig. 11. Probe in the Ice at a Depth of about 3 Meters.

Despite the failures, the probe exhibited substantial robustness through its ability to degrade gracefully with no catastrophic single-point failures surfacing. The complete data set will allow the team to finalize:

1. Comparison of actual melt efficiency with modeled melt efficiency (to allow adjustment of Mars power requirements);
2. Assessment/derivation of vehicle control algorithms based on actual vehicle behavior; and
3. Derivation of fault recovery paradigms based on actual vehicle failure mode data.

The test results will support the development of the vehicle autonomous control system and will provide insight into how to configure the flight probe. After completion of the 23-m glacier penetration, the probe was retrieved from the ice by employing a hot-water drill to re-open the melt column. The cryobot was then hoisted out of the melt column using the tripod mounted stepper motor.

6. Conclusions

In conclusion, the FY'01 Cryobot prototyping effort has resulted in a successful probe development and test. Ice penetration with varying degrees of dust/particulate loading has been characterized. The overall probe development activity proceeded much farther than originally planned for FY'01. Not only was the complete control system built along with all of the sensor elements, but the combined passive and active melt systems were implemented along with the design and accommodation of the two science instruments. Separate work was initiated in the area of acoustic imaging through a partnering arrangement with RESON Hydro-acoustics. This research will be reported in subsequent publications. Finally, the Cryobot system was developed to a point at which the complete integrated system could be deployed in the field. FY'02 research will push the probe development towards more robust dust/ particulate management, greater autonomous control, and integration/test of the first generation of micro-acoustic imagers.

7. Acknowledgements

The cryobot research and development effort was jointly funded by NASA Code R and Code S (Outer Planets). The field trip was largely funded by the NASA Code S Discovery Scout Program. The Cryo-Scout mission concept is a team effort composed of several university researchers, JPL researchers, NASA Glenn, NASA Ames, and Lockheed Martin, Denver. The Cryobot robotic vehicle development effort includes several other notable individuals: J. Feldman, mechanical engineering; G. French and C. Harmon, system engineering/test; P. Shakkattai, fluid dynamics modeling; R. Ivlev and W. Fang, electronics design/engineering; F. Nicaise, camera/housing design; D. Svehla, GSE design; J. Tarsala, tether design; J. Toczylowski, electrical power system design/test; M. Roy and Q. Ng, tech support; D. Helmick, vehicle control system design/software engineering; chemistry sensor provided by ORION; and ice-wall camera provided by A. Lane.

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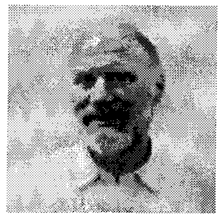
9. Biographies

Wayne Zimmerman *has been a senior engineer at the Jet Propulsion Laboratory/California Institute of Technology, for more than two decades. He received his B.S. in Fluid Dynamics with a major in Aerospace Engineering from Case Institute of Technology, Cleveland, Ohio in 1969. He received his M.S. in System Engineering/Management from* the University of Southern California, Los Angeles California in 1972. He has been working in robotics for 22 years and was the Project Element Manager (PEM) for the Mars '98 Polar Lander Robotic Arm. He was also the Avionics PEM/Lead Engineer for the Mars '01 Micro-Rover and Robotic Arm. He currently holds a joint position as Lead Engineer for the Mars/Europa Cryobot Task and Lead Engineer for the JPL Center for In Situ Exploration and Sample Return (CISSR). Wayne is responsible for spearheading advanced robotic vehicle and sampling/ sample handling system designs, which are enabling for out-year NASA missions to extreme environments, such as Europa, Venus, Titan, and comets. He has published over 55 technical papers and co-authored two books in the field of robotics.

F. Scott Anderson, a planetary geophysicist, geologist, and remote sensing scientist, is experienced in a wide range of data analysis and mission efforts. He is the Gamma Ray Spectrometer Investigation Scientist for the 2001 Mars Odyssey mission at the Jet Propulsion Laboratory/California Institute of Technology. He also provides science support for JPL's Cryobot team regarding Mars Polar ice, reduction of TES data for radiative transfer modeling, MOLA data analysis, MOC and MOLA interpretation, and numerical modeling of climate on surface geologic expression for both Venus and Mars. Scott is also active in the field of geophysics and tectonics; he explores analytical models of admittance and flexure, as well as finite element models of lithospheric deformation

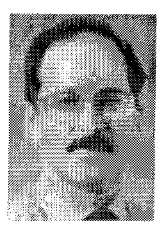
Frank Carsey is engaged in developing sub-glacial exploration programs for Earth, Mars, and Europa. During his 20 years at the Jet Propulsion Laboratory/California Institute of Technology, he has been Group Supervisor for Oceanography, Team Leader for Polar Oceanography, Task Scientist for the Alaska Synthetic Aperture Radar (SAR) Facility, and Principal Investigator on several missions and tasks. Before coming to JPL, he had appointments at the National Oceanic and Atmospheric Administration (NOAA) Environmental Research Laboratories, the University of Washington, the NASA Goddard Space Flight Center, and NASA Headquarters. Frank received his Ph.D. in Physics from UCLA in 1971 and has focused his career in polar science, primarily sea ice and ice sheets.

Pamela Conrad is a geobiologist in the Center for Life Detection at the Jet Propulsion Laboratory/California Institute of Technology in Pasadena, CA. Although trained in mineral physics, her present research interests are geobiological, that is, interdisciplinary in nature, in the basic science sense, and astrobiological in the applied sense. The common theme is interpreting chemical evidence of the activities of life in the geologic record. Major areas of inquiry include (1) the geochemistry and preservation of organisms that live in rock and sediment (including ice), (2) the development of analytical probes for measurement of interactions between organisms and minerals at various spatial and temporal scales, and (3) the nature, diversity and behavior of antifreeze biomolecules in cold-adapted micro-organisms.



Hermann Engelhardt has worked on ice most of his life. He obtained his Ph.D. in Physics from the University of Munich (München) in Germany on the subject of "Proton Conductivity of Ice." As a postdoc, he discovered Ice IV in Ottawa, Canada. He was a professor at the Universities in München, Münster, Zürich, and Cali (Colombia). He is currently a Senior Research Associate in Geophysics at the California Institute of Technology. In the late 1960s, Hermann organized the First International Symposium on the Physics of Ice. Since 1988 he organized 13 expeditions to Antarctica to study the West Antarctic Ice Sheet, especially its fast moving ice streams.

Lloyd French is Task Manager at the Jet Propulsion Laboratory/California Institute of Technology for the Active Thermal Probe sponsored by the Cross-Enterprise Technology Development Program (CETDP). He previously served as lead engineer for the Underwater Volcanic Vent Probes. Lloyd is one of the first graduates of JPL's Systems Architect Development Program. He works closely with the Center for Space Mission Architecture and Design (CSMAD) and the Center for In Situ Exploration and Sample Return (CISSR), and he maintains a Thermal Environment Lab with a Mars Environment Chamber. Lloyd lectures at the International Space University on thermal spacecraft design and mission design. He holds degrees in Mechanical Engineering from the University of California-Berkeley in the areas of Heat Transfer and Control Systems.



Michael Hecht, a physicist at the Jet Propulsion Laboratory, has at various times worked on semiconductor surface and interface science, planetary science, MicroElectroMechanical (MEMS) Systems, and scientific instrument development. He was most recently the project manager for the Mars Environmental Compatibility Assessment, a soil analysis payload intended to fly on the cancelled Mars Surveyor Program (MSP) 2001 Lander. Previously, Dr. Hecht established and led a multi-institutional Integrated Product Development Team (IPDT) for in situ instruments under the New Millennium Program. He has designed, built, and operated several highly sophisticated laboratory instruments for materials analysis, has published extensively in several fields, and was the first recipient of JPL's Lew Allen Award for Excellence.